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NOTCH-TIP DAMAGE AND TRANSLAMINAR FRACTURE TOUGHNESS MEASUREMENTS FROM CARBON/EPOXY LAMINATES

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13. ABSTRACT *(Maximum 200 words)*

Notched [0/+45/90/-45] carbon/epoxy laminates were used to study translaminar fracture, where through-thickness cracking propagates across fibers and laminae. Radiographs of damage were compared with crack growth determined from load-versus-deflection plots using elastic fracture mechanics. Comparison of damage at the notch tip with fracture mechanics evaluations identified some material/test conditions for which a critical value of fracture toughness is a useful concept. For other conditions, the extent of damage in the specimen showed that the concept of fracture toughness is not directly applicable.

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INTRODUCTION

Over the past decade there has been considerable interest in interlaminar fracture toughness of carbon/polymer laminates, where delamination fracture between laminae is an important failure mode. For example, the work of O'Brien and coworkers (ref 1) described some of the large body of work on the development of tests and analysis methods for characterizing interlaminar fracture toughness. There has also been interest in investigating translaminar modes of fracture in composite laminates, where through-thickness cracking propagates in a self-similar manner across fibers and laminae.

The work of Harris and Morris (refs 2,3) was an important impetus to translaminar fracture investigations. Their work included comprehensive testing and analysis of a variety of laminated composites and test configurations.

In recent work by the current authors, the terminal damage state of notched carbon/epoxy laminates has been monitored using real-time radiography (ref 4), and the fracture strength and load-displacement behavior of similar laminates has been measured (ref 5). The general objective of this study was to combine and extend these two approaches in an investigation of translaminar fracture of composite laminates. The specific objective was to determine whether or not linear elastic fracture toughness test methods give a useful measure of critical failure load for a given range of test configurations of a quasi-isotropic carbon/epoxy laminate. The methods used for performing and analyzing the fracture toughness tests were essentially those developed for K_{Ic} tests of metals, whereas the method used for characterizing the progression of damage during the tests is a specialized radiographic technique developed for composite laminates (ref 4).

MATERIAL AND TEST PROCEDURES

The laminate used was a quasi-isotropic $[0/+45/90/-45]_{4S}$ layup of AS4 carbon fiber/977-2 toughened epoxy, with all specimens cut from a 0.45 m by 0.50 m, 4.2-mm thick plate. The so-called compact tension specimen configuration was used for the fracture tests, as shown in Figure 1. This configuration is more efficient in the use of test material than the bend or tensile panel configurations, and the stress intensity, K, and crack-mouth displacement, d, relationships for this configuration are available for use in analysis of test results, as described later. Note in Figure 1 that 60-degree "knife" edges have been machined into the specimen at the crack mouth as attachment points for the "clip gauge" commonly used in fracture testing. This measurement of displacement directly at the crack mouth is important to prevent any extraneous displacements, such as those associated with the pin loading, from interfering with the characterization of notch-tip damage. The damage and apparent crack growth are inferred from crack-mouth displacement, as discussed later, so this displacement should exclude extraneous inputs as much as possible. Note also in Figure 1 the notch thickness differences among specimens, which may contribute to differences in test results.

A list of tests performed and typical load, P, versus crack-mouth displacement, d, results from a test are shown in Table 1 and Figure 2, respectively. Specimens #1 through 4 were tested at the University of Toronto, including load interruptions, to allow measurement of specimen damage by a radiographic method, at points a, b, and c in Figure 2, for example.

Specimens #5 through 8 were tested at Benét Laboratories and unloaded at a point such as point b in Figure 2 for measurement of damage.

Both post-loading and quasi-real time radiography were used to monitor damage in this study. During the quasi-real time tests, load was applied using a small tensile fixture that fit into the chamber of a Scanray Corporation Torrex 120D X-ray machine and included a reservoir of zinc iodide penetrant. Specimens were held in a set of wedge grips, and loads of up to 5 kN were measured with an accuracy of 20 N using a strain gauge circuit. The tests were interrupted after a noticeable drop in load, the reservoir of penetrant was removed, and the notch was rinsed and dried. The entire fixture, with the specimen still under load, was transferred to the X-ray machine, and a contact print of the specimen was taken. Dupont NDT 55 film was used with exposure times of about 2 minutes for X-ray tube settings of about 25 kV and 3 mA. The notch was then re-immersed in penetrant, and the procedure was repeated. Radiographs of specimens subjected to a given load and displacement in a conventional testing machine were taken by soaking the specimens for 30 minutes in zinc iodide penetrant and subsequently radiographing them in the standard way.

FRACTURE TESTS AND DAMAGE MEASUREMENTS

Measured Elastic Modulus

Each fracture test began with a linear elastic section of the P versus d trace, as shown in Figure 2, from which crack-mouth compliance, d/P, can be directly measured (see Table 1). The average elastic modulus, E, of the laminate can be calculated from d/P and the initial value of relative notch length, α = a/W, using the following relationship, taken from an ASTM fracture toughness test procedure (ref 6);

$$E = [P/dB][(1+\alpha)/(1-\alpha)]^2[2.163 + 12.219\ \alpha - 20.065\ \alpha^2 - 0.9925\ \alpha^3 + 20.609\ \alpha^4 - 9.9314\ \alpha^5] \tag{1}$$

where B is the 4.2-mm specimen thickness mentioned earlier. The calculated modulus for each specimen is listed in Table 1. Note that the mean values from the two specimen groups are in close agreement, and that all the E results are in the expected range for this type of material; a value of 55.6 GPa was reported for [0/±45/90] carbon/epoxy in Reference 2. For the quasi-isotropic laminates of this study and that of Reference 2, the use of Eq. (1), which applies for an isotropic elastic material, is believed to be appropriate.

Table 1. Comparison of Test Conditions and Elastic Modulus and Maximum Load Measurements

Specimen Number	Relative Notch Length, a/W	Crack-Mouth Compliance, a/P mm/kN	Elastic Modulus, E GPa	Maximum Load, P_{max} kN
1	0.510	0.222	61.4	4.44
2	0.510	0.227	60.0	4.20
3	0.502	0.255	51.7	4.26
4	0.529	0.271	55.0	3.84
			mean: 57.0	
5	0.500	0.233	56.1	3.92
6	0.390	0.139	59.7	5.50
7	0.560	0.296	58.4	3.39
8	0.370	0.129	59.7	6.03
			mean: 58.5	

Critical Applied K Values

Values of applied K were calculated for various points of interest on the P-d plot, such as the point of maximum load or the point after a sudden drop in load, often called a pop-in. These K values are summarized in Table 2 along with the amount of deviation, x, from the elastic straight-line portion of the P-d plot (see Figure 2). The value of x at a given point on the P-d plot is important because it accounts for the increment of displacement that has occurred up to that point in the test. Dawes (ref 7) recently emphasized the importance of accounting for displacement as well as load effects in analyzing pop-in behavior during a fracture toughness test. Referring again to Figure 2, the tests here showed a series of abrupt decreases in load and related increases in displacement typical of the pop-in behavior sometimes observed in fracture tests. To quantitatively describe these abrupt changes, an approach similar to that of Reference 7 was used to write an expression for the elastic crack-mouth compliance associated with any given point on the P-d plot, $(d/P)_i$, as follows;

$$(d/P)_i = (d/P)_o + x_i/P_i \tag{2}$$

where $(d/P)_o$ is the initial measured compliance and x_i and P_i are the permanent crack-mouth displacement and load values of the point under consideration on the P-d plot. The compliance for the point was then used to calculate the increase in relative crack length, a_i/W, for that point, using the relation for the compact tension specimen given in Reference 6, as follows:

$$a/W = 1.000196 - 4.06319\,u + 11.242\,u^2 - 106.043\,u^3 + 464.335\,u^4 - 650.677\,u^5 \tag{3}$$

where

$$u = 1/[(BEd_i/P_i)^{1/2} + 1] \tag{4}$$

The approach outlined by Eqs. (2) through (4) requires the assumption that the change in specimen compliance results only from crack extension under elastic conditions and not from permanent deformation at the notch tip. One indication of the degree of elastic crack-extension control in the tests is the degree of coincidence of the P-d traces at points a and b in Figure 2 and at the zero-load points following the unloadings. Permanent deformation at the notch tip, such as the plastic deformation of metals, would cause large permanent offsets at these points. Note that, although there is not exact coincidence at these points, the offsets are small relative to those which would have resulted if all the deformation were permanent.

Table 2. Calculated Values of Applied K at Various Points on the Load-Displacement Plots

Specimen Number	At P_{max}, x=0 $K_{max\text{-}o}$ MPa√m	At P_{max} x mm	At P_{max} K_{max} MPa√m	After Pop-in x mm	After Pop-in K_{pop} MPa√m	At Unload x mm	At Unload K_{ul} MPa√m
1	65.8	0.15	72.8	0.45	85.0	-	-
2	62.3	0.09	66.5	0.24	72.6	-	-
3	68.0	0.17	68.0	0.34	74.0	0.28	70.9
4	64.2	0.09	64.2	-	-	0.20	67.8
	mean: 65.1 standard deviation: 2.4						
5	56.3	0.13	61.6	0.19	64.0	0.24	63.0
6	58.1	0.09	62.6	-	-	0.13	62.5
7	59.3	0.15	65.5	0.27	69.9	0.34	62.4
8	60.4	0.13	66.9	0.19	70.0	0.23	69.6
	mean: 58.5 standard deviation: 1.8						

Referring again to Table 2, the K values listed with $x > 0$ include the apparent increase in crack length calculated by compliance analysis (Eqs. (2) through (4)) of the P-d plot. Two trends in the results are noteworthy. First, the K values at maximum load using the initial notch length, designated $K_{max\text{-}o}$, are noticeably higher for specimens #1 through 4, compared with #5 through 8. This may be due to the wider notch for specimens #1 through 4, noted in Figure 1. A similar trend was noted in earlier work (ref 5), where an increase in notch width from 0.6 to 6 percent of the specimen width was accompanied by a 29 percent increase in fracture toughness. Here, an increase in notch thickness from 1 to 3 percent of W resulted in an 11 percent increase in fracture toughness. A second trend to note is the tendency toward higher applied K for

increased amounts of deviation, x, from the initial linear portion of the P-d trace. This suggests that increasing K-resistance curve behavior is present in these materials, that is, the fracture toughness increases with increasing amounts of damage and apparent crack growth. This is considered further in an upcoming discussion.

Damage and Crack Growth

Figures 3 and 4 show radiographs of the damage that occurred ahead of the notch tip for four of the specimens tested. Specimen #3 was radiographed after various load intervals. The 3.6 and 3.9 kN results indicate a growing but still contained zone of damage at the notch tip, whereas the 1.1 kN radiograph shows damage fully across the specimen. Specimens #4, 6, and 7 show the typically contained damage present after unloading from a point with $x = 0.1$ to 0.3 mm; note that the damage in specimens #6 and 7, with significantly different a/W, is still generally similar in nature.

A comparison of various determinations of notch-tip damage and crack growth from the tests and calculations is shown in Figure 5. Three types of crack-growth measurements are compared with the calculation of crack growth using the method described in relation to Eqs. (2) through (4).

1. The simplest determination of damage and crack growth is a visual measurement. Such measurements were made with a 20X microscope on both surfaces, and the larger of the two surface measurements is shown.

2. The extension of the notch visible on the radiograph is also shown; the total extent beyond the original notch tip of the dark damage zone (see Figures 3 and 4) was measured.

3. The crack growth determined from the measured unloading compliance is shown using Eqs. (3) and (4) to calculate the crack growth at the point of unloading.

It is clear from Figure 5 that the crack growth from unloading compliance gives the closest agreement with the P-d curve calculation of crack growth; the least squares regression line of unloading crack growth versus P-d curve crack growth is close to the dashed line which indicates exact agreement. The relatively large surface measurements of crack growth are not surprising, because damage is often more extensive in outer plies of a laminate. The somewhat larger X-ray damage zones relative to calculated crack growth may indicate that damage is not severe enough in the outer portion of the damage zone to effectively extend the crack. The results show that the amount of calculated crack growth corresponds to approximately 80 percent of the extent of damage zone indicated by the radiographs.

A description of notch-tip damage and crack growth over a considerable range of applied load and crack-mouth displacement is presented in Figures 6 through 8. First, in Figure 6, the upper portions of the P-d plot of specimen #8 is shown, which is representative of the step-like pop-in behavior observed in this study. The points of significant change in the plot were numbered 1 through 12 and plotted as applied K versus d in Figure 7, where the value of applied K was calculated by including the increment of apparent crack growth that had occurred at each of the twelve points. Equations (2) through (4) were used, as discussed earlier. Results from

another specimen #2 with different a_o/W are also shown in Figure 7 using the same procedure. The fact that the K-d plots are monotonically increasing in a smooth manner supports the earlier suggestion that crack extension under elastic conditions controls the P-d behavior in these tests, since it was an elastic crack-extension analysis that produced the smooth K-d plots. This line of reasoning is taken a step further in Figure 8, where the data of Figure 7 are plotted in the usual crack-growth resistance, K_R, form of applied K versus crack growth. Results from the two specimens, which have quite different starting notch lengths, are fairly well represented by the power law curve shown on the plot. It is not apparent at this point what significance there is to the type of K_R curve that happened to represent the results. However, since an elastic crack-extension analysis was used to calculate the K_R curve, this is another indication that elastic crack-extension controls the fracture behavior of these laminates. It should also be noted that others have discussed this type of increasing crack-growth resistance in fracture tests of laminates. Kortschot and Beaumont (ref 8) described a decrease in the maximum stress at the notch as damage, and notch-tip blunting occurred, which would result in increasing resistance to crack growth as damage proceeded.

SUMMARY

1. The compact tension specimen with integral crack-mouth displacement measurement using a "clip gauge" and calculation of applied K using an isotropic K solution gives a useful measure of fracture toughness for this quasi-isotropic laminate. The measured initial compliance of the notched specimen gives consistent elastic modulus results that are in close agreement with results from the literature. Fracture toughness determined from maximum load attained in the test and the initial notch length showed the expected variation with notch width; mean toughness values of 58.5 and 65.1 MPa√m were observed for the 0.3 and 0.8-mm width notches, respectively, with standard deviations of less than 4 percent of mean for both sets of tests.

2. Crack growth determined from the P-d curve using an elastic crack-growth compliance analysis agrees well with crack growth determined from elastic unloading compliance of samples that were unloaded before final failure. Direct comparisons of P-d curve and unloading compliance determinations of crack growth with radiographs of damage showed that crack growth corresponded to approximately 80 percent of the extent of damage zone.

3. Abrupt pop-in-type changes in the P-d curves were noted and were found to correspond to a smooth, continuously increasing K-d plot and an increasing crack-growth resistance curve of the K versus Δa type observed with some metals. Since elastic crack-growth compliance analysis was used to calculate K and Δa, the consistent results indicate that elastic crack extension controls the fracture behavior of this type of laminate.

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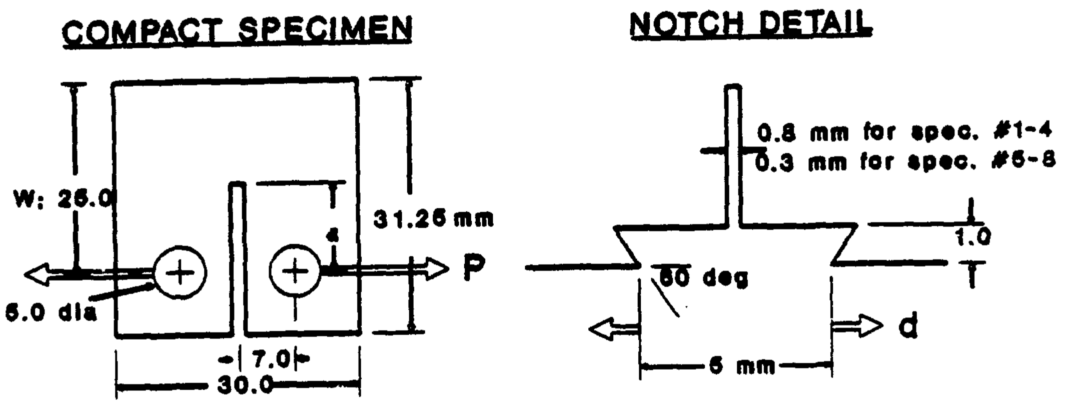


Figure 1. Specimen configuration and nomenclature.

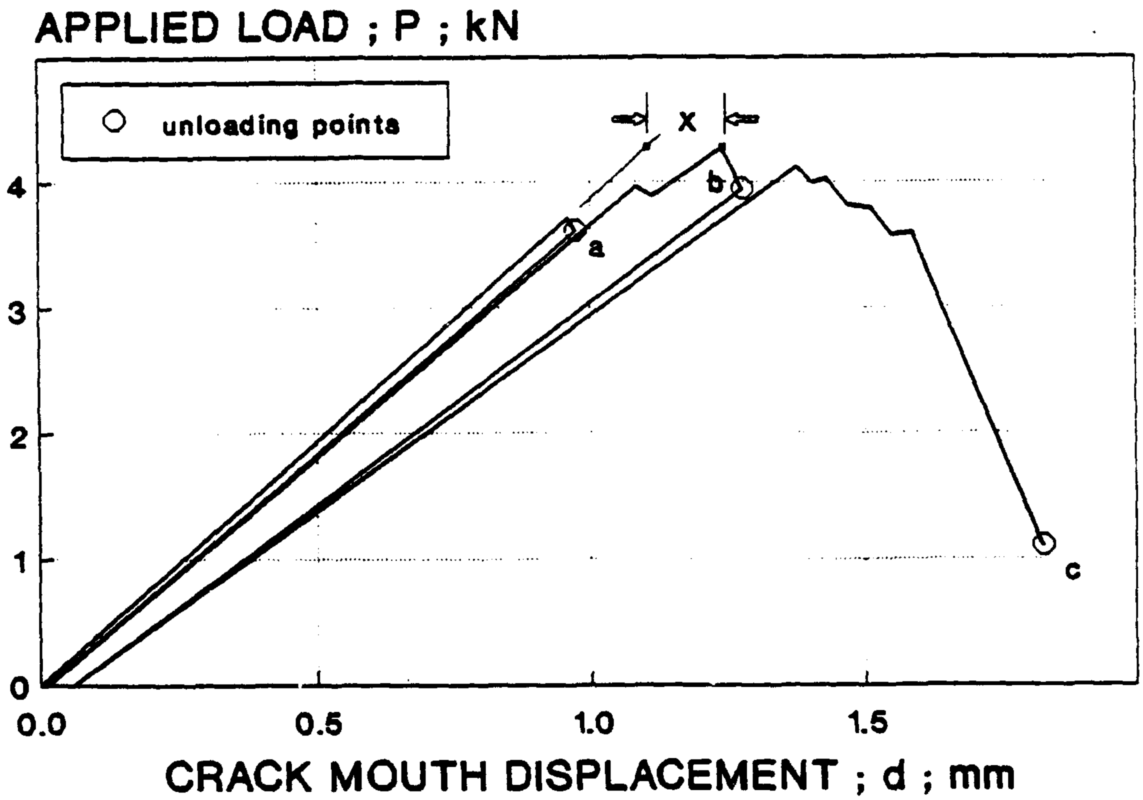
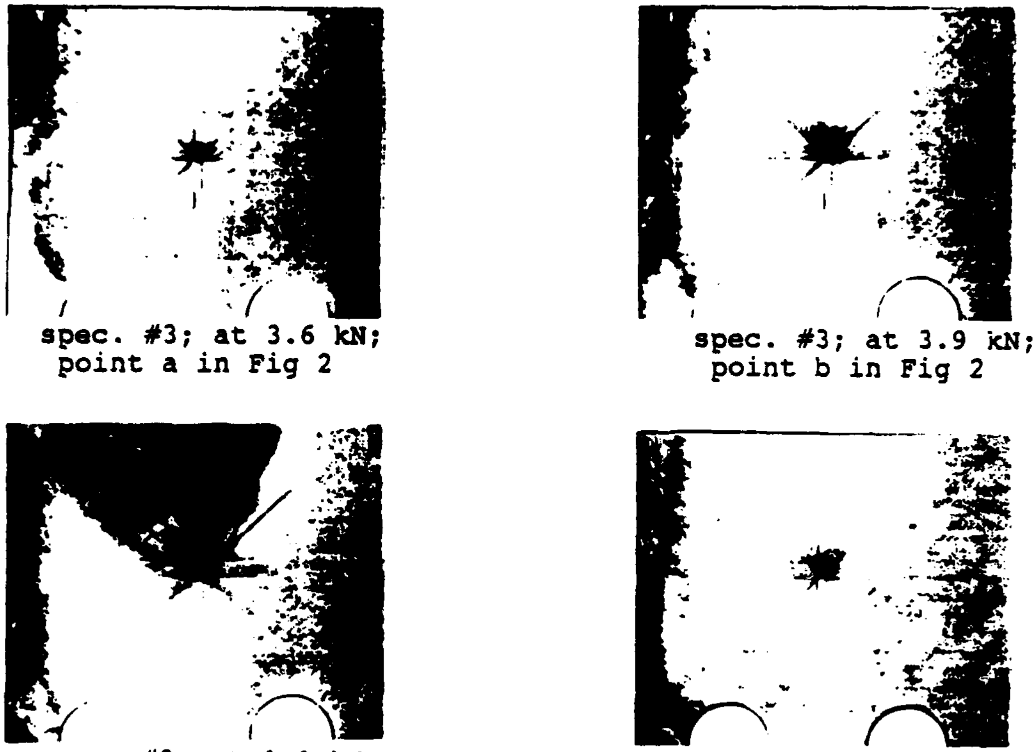


Figure 2. Load versus crack-mouth displacement behavior: specimen #3.



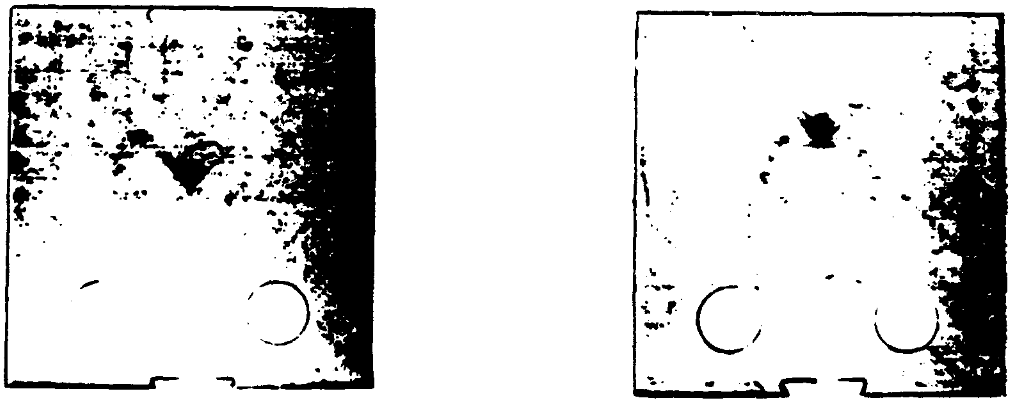
spec. #3; at 3.6 kN;
point a in Fig 2

spec. #3; at 3.9 kN;
point b in Fig 2

spec. #3; at 1.1 kN;
point c in Fig 2

spec. #4; at 3.7 kN;
point of unload

Figure 3. Radiographs of notch-tip damage at various intervals of loading.



spec. #6; at 5.0 kN
$a_0/W = 0.39$

spec. #7; at 1.8 kN
$a_0/W = 0.56$

Figure 4. Radiographs of notch-tip damage at point of unloading.

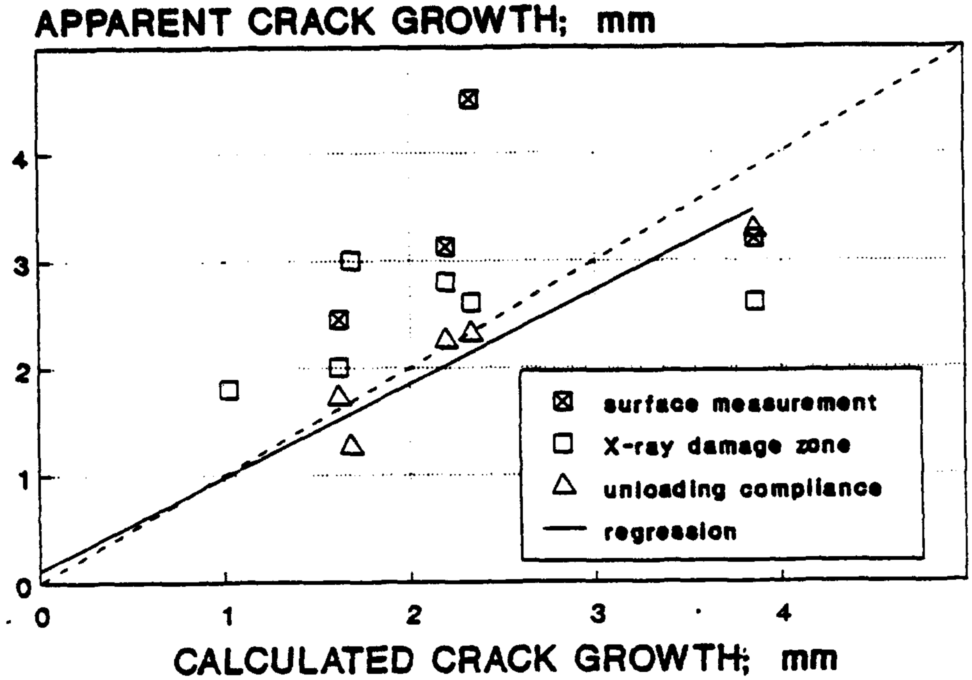


Figure 5. Comparison of crack growth by various determinations.

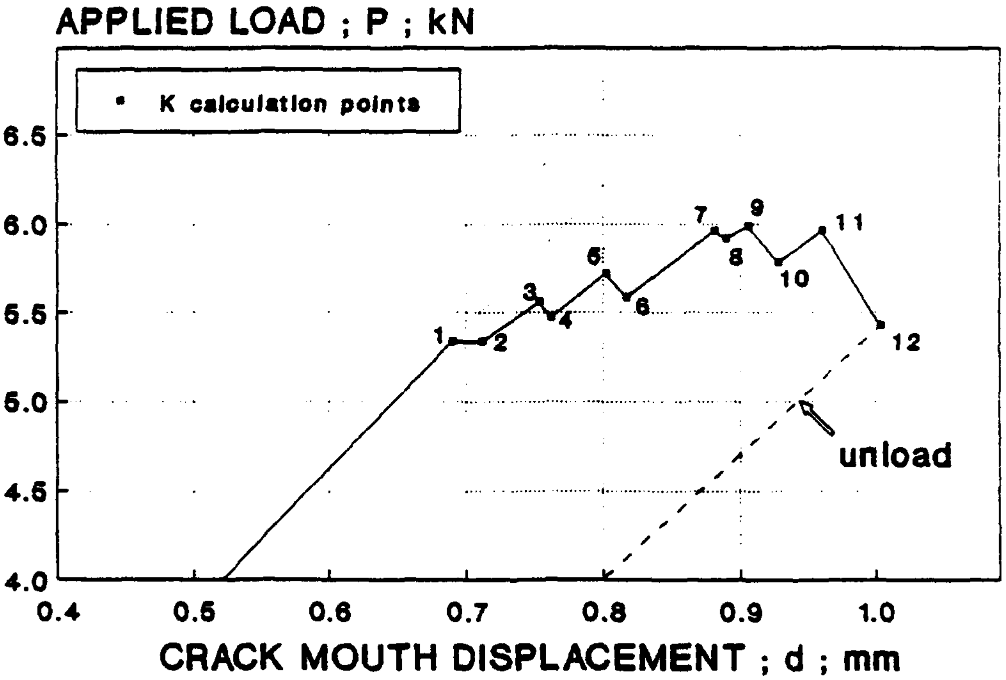


Figure 6. Load versus crack-mouth displacement behavior: specimen #8.

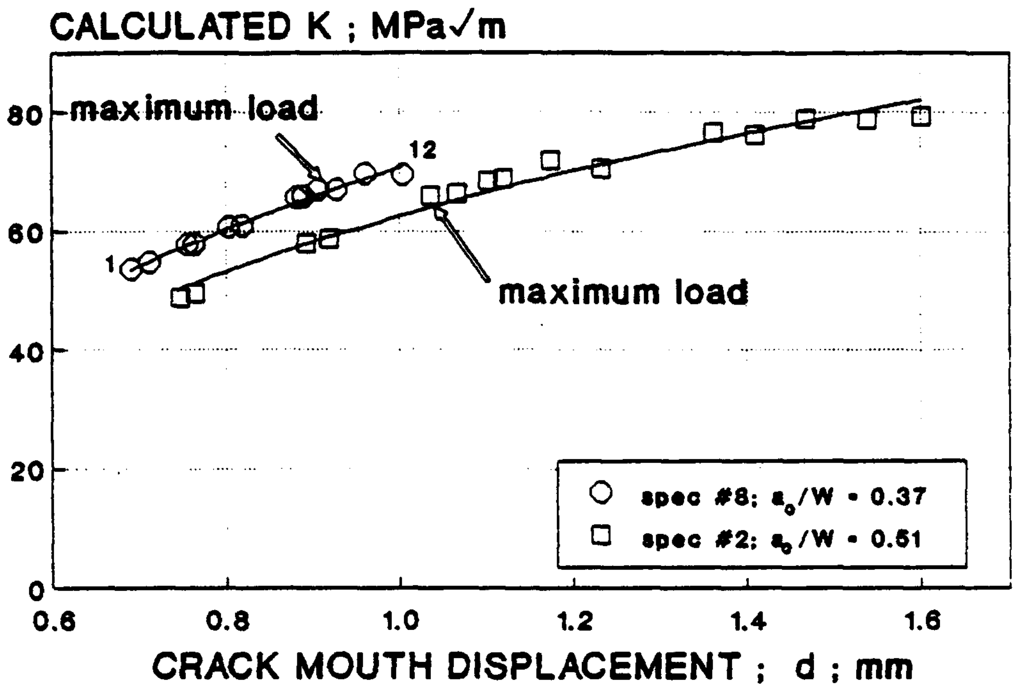


Figure 7. Calculated K from P-d plot versus crack-mouth displacement.

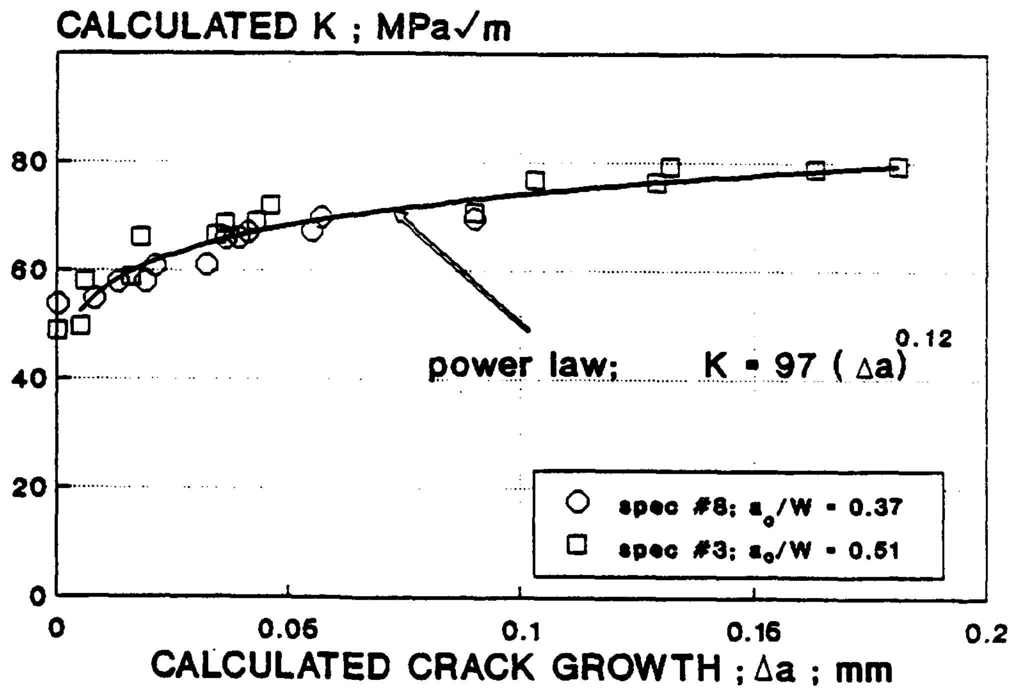


Figure 8. Calculated K from P-d plot versus calculated crack growth.

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